NASA Engineering and Safety Center (NESC) Consultation on Cracking in Shuttle Orbiter's Reaction Control System (RCS) Thrusters

Dr. Rebecca MacKay

Materials and Structures Division

September 8, 2006

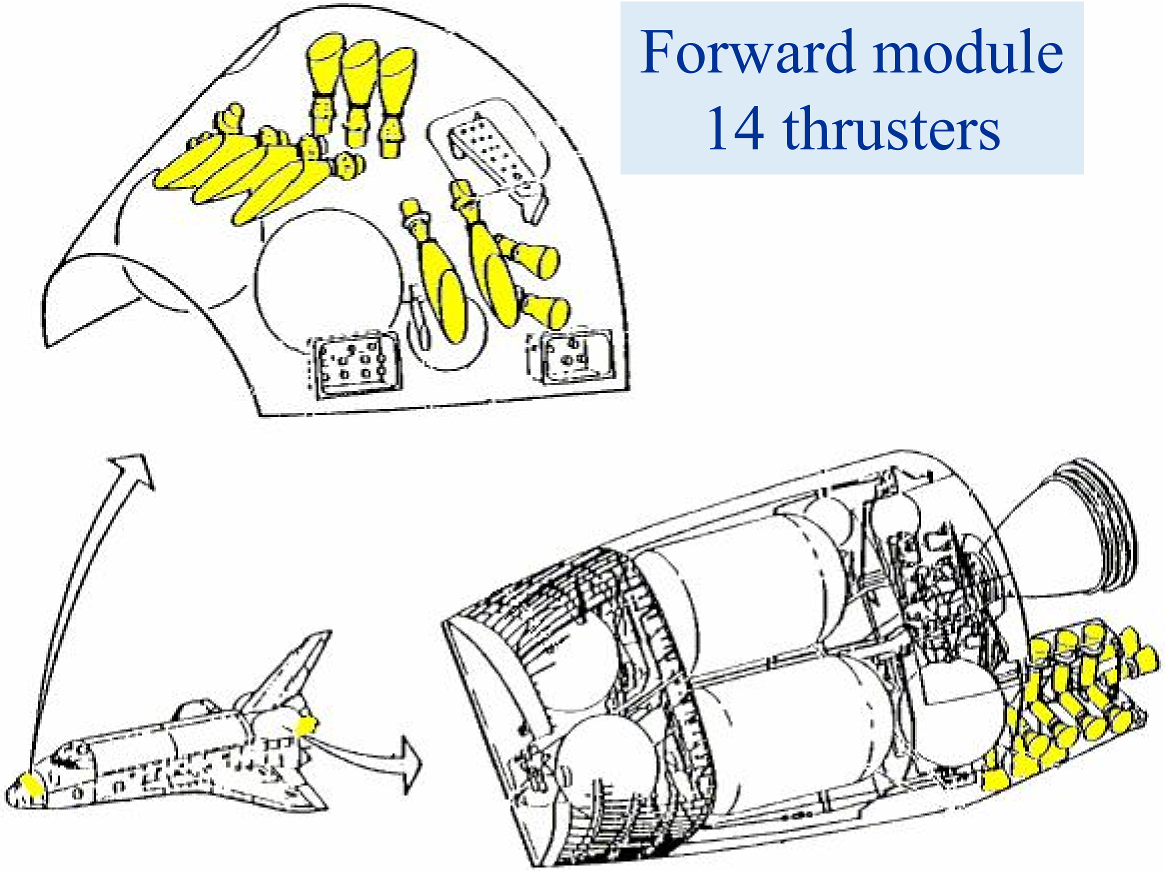
Steven Smith (LaRC), Sandeep Shah (MSFC), and Robert Piascik (NESC)

Acknowledgements

Special thanks to:
David Hull (GRC), Terry McCue (GRC-Arctic Slope), James Smith (formerly GRC-QSS), and Robert Titran (GRC, retired)

Binayak Panda (MSFC)
Andy Newman (LaRC)
Dave Brinkman (GRC-SLI)
Joy Buehler (GRC-Arctic Slope)
Derrick Cheston (NESC)
Anita Garg (GRC-U.Toledo)
Hugh Gray (GRC)
Dereck Johnson (GRC)
Pete Kantzos (formerly OAI)
Greg Jerman (MSFC)
Susan Gavin (JSC-S&MA)
Bill Karpinski (GRC-Arctic Slope)
Mike Nathal (GRC)
Jami Olminski (formerly QSS)
Santo Padula (GRC)
Aldo Panzanella (GRC-GLCR)
Frank Ritzert (GRC)
Tim Ubienski (GRC-SLI)

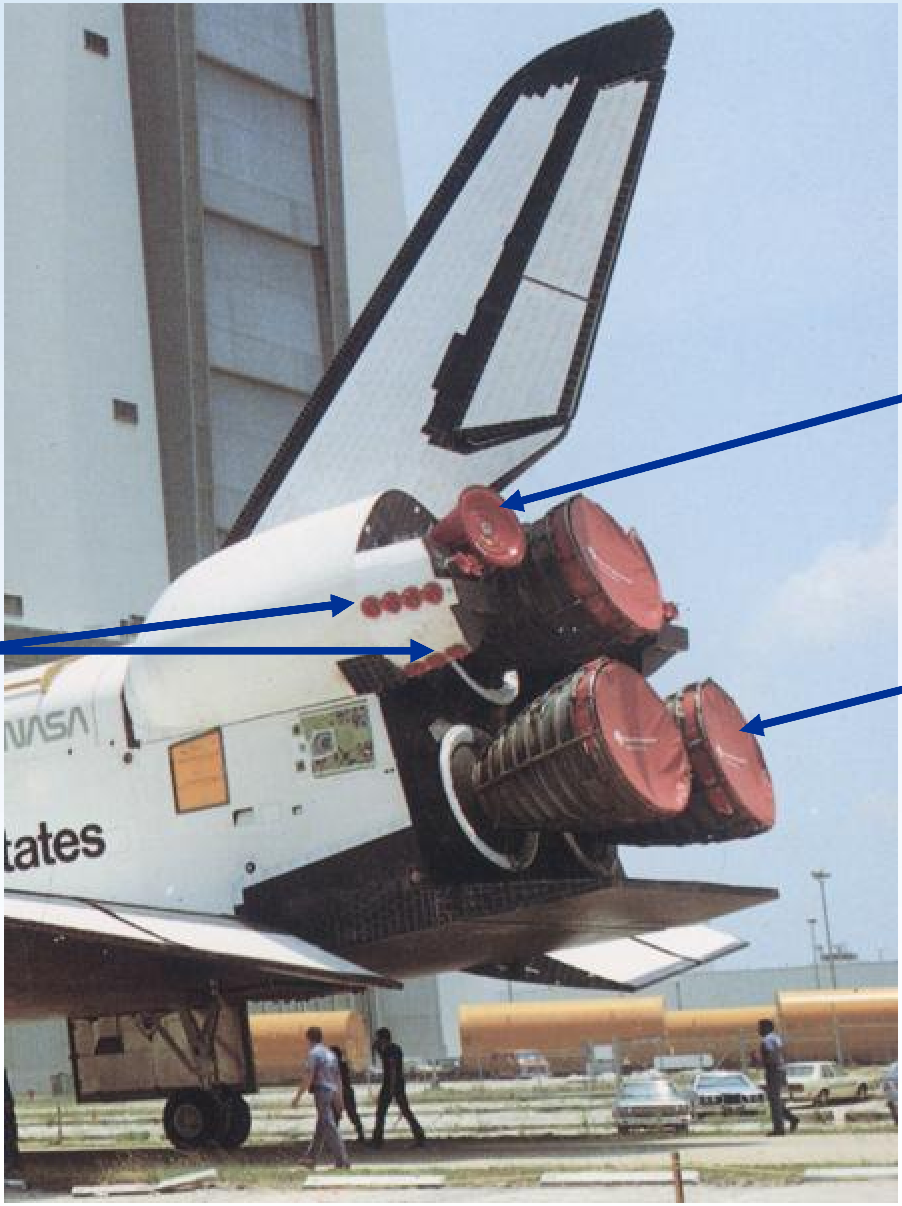
Primary RCS Thruster Locations



Forward module
14 thrusters

Two aft modules
12 thrusters each

Aft Section of the Space Shuttle Orbiter



38 RCS Thrusters

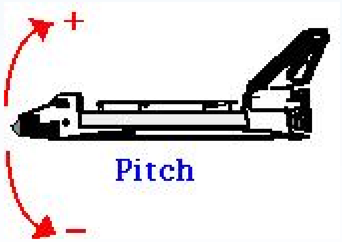
2 OMS (Orbital Maneuvering System) Engines
Provide additional thrust to get into orbit

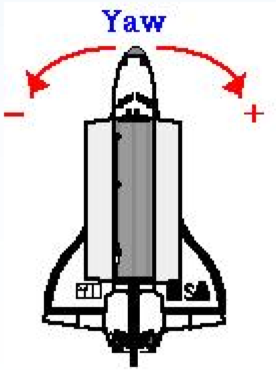
3 Space Shuttle Main Engines
Provide thrust during launch

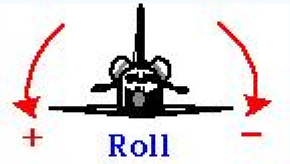
Photo from Aerojet.com

Thruster Facts

- Thrusters operate by pulse firing
  - Propellants are hypergolic and ignite upon contact
- Thrusters guide the orbiter in space and provide:
  - Attitude maneuvers (pitch, yaw, and roll)
  - Translation maneuvers (small velocity changes along orbiter axis)
- Mission success for every shuttle flight depends on thrusters
  - Separation sequence for external tank separation
  - Rendezvous Pitch Maneuver
  - Docking on International Space Station
  - Initial reentry sequence

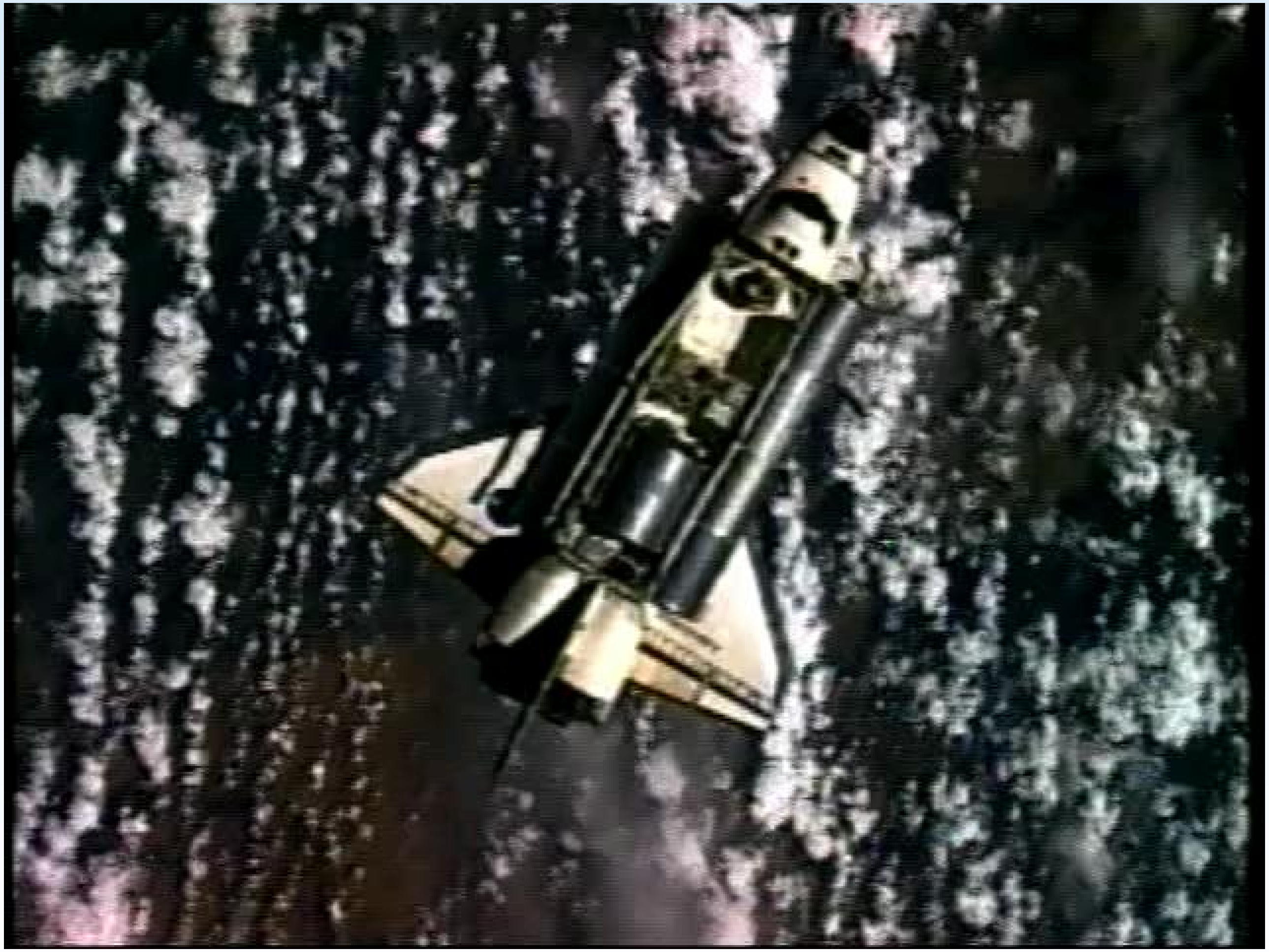






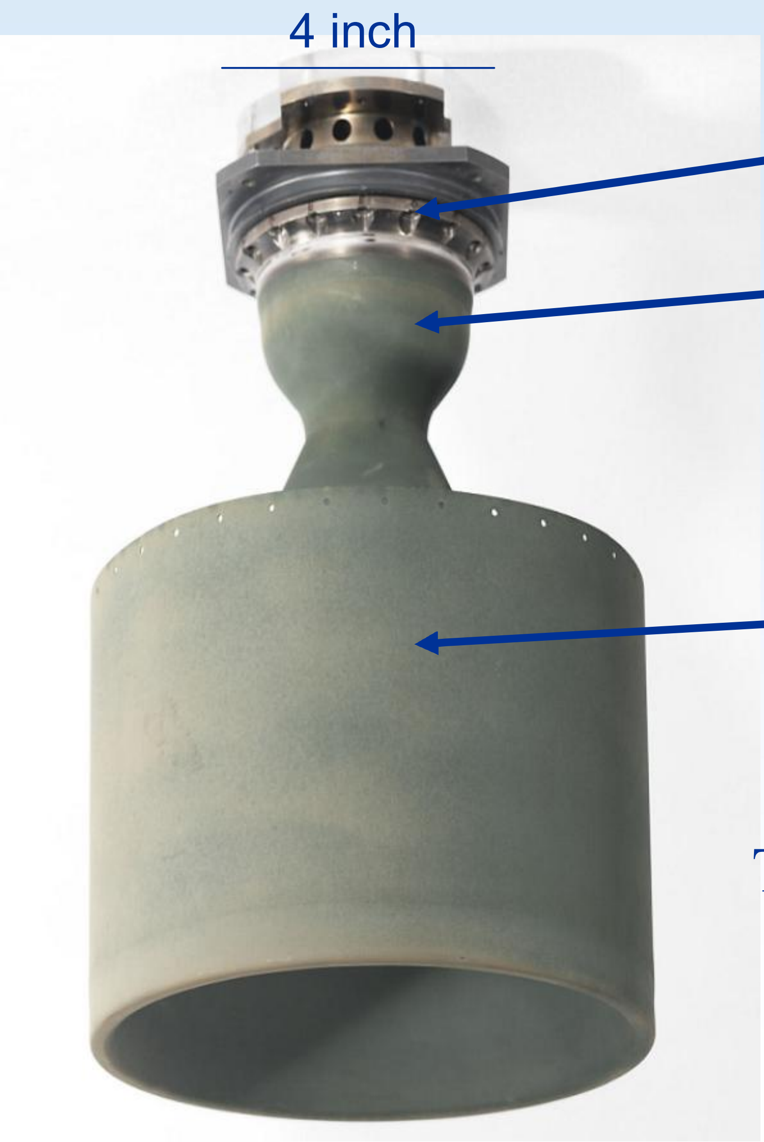
From liftoff.msfc.nasa.gov

Footage of Actual Pitch Maneuver on STS-114



- Occurred 600 feet away from International Space Station
- Provided 90 seconds to photo underside of Discovery

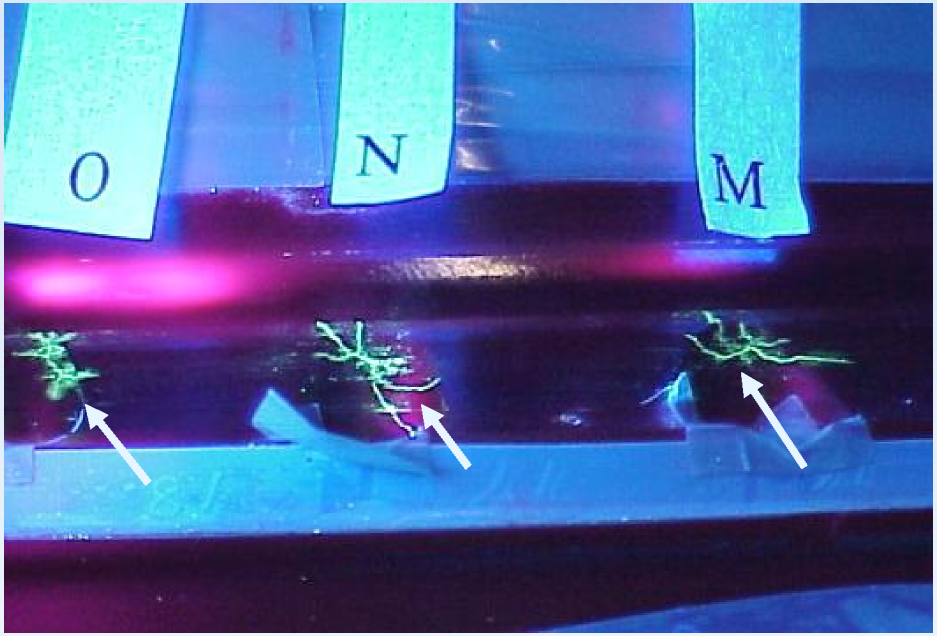
RCS Thruster Components



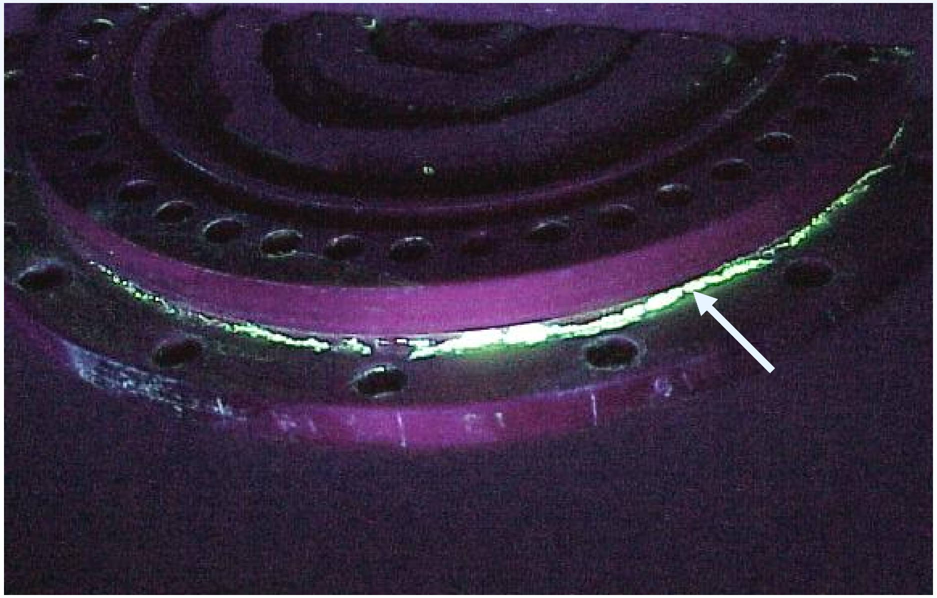
Thrusters were designed for 100 missions

Photo from Boeing-Huntington Beach

Thruster Cracking Observed



Counterbore cracks

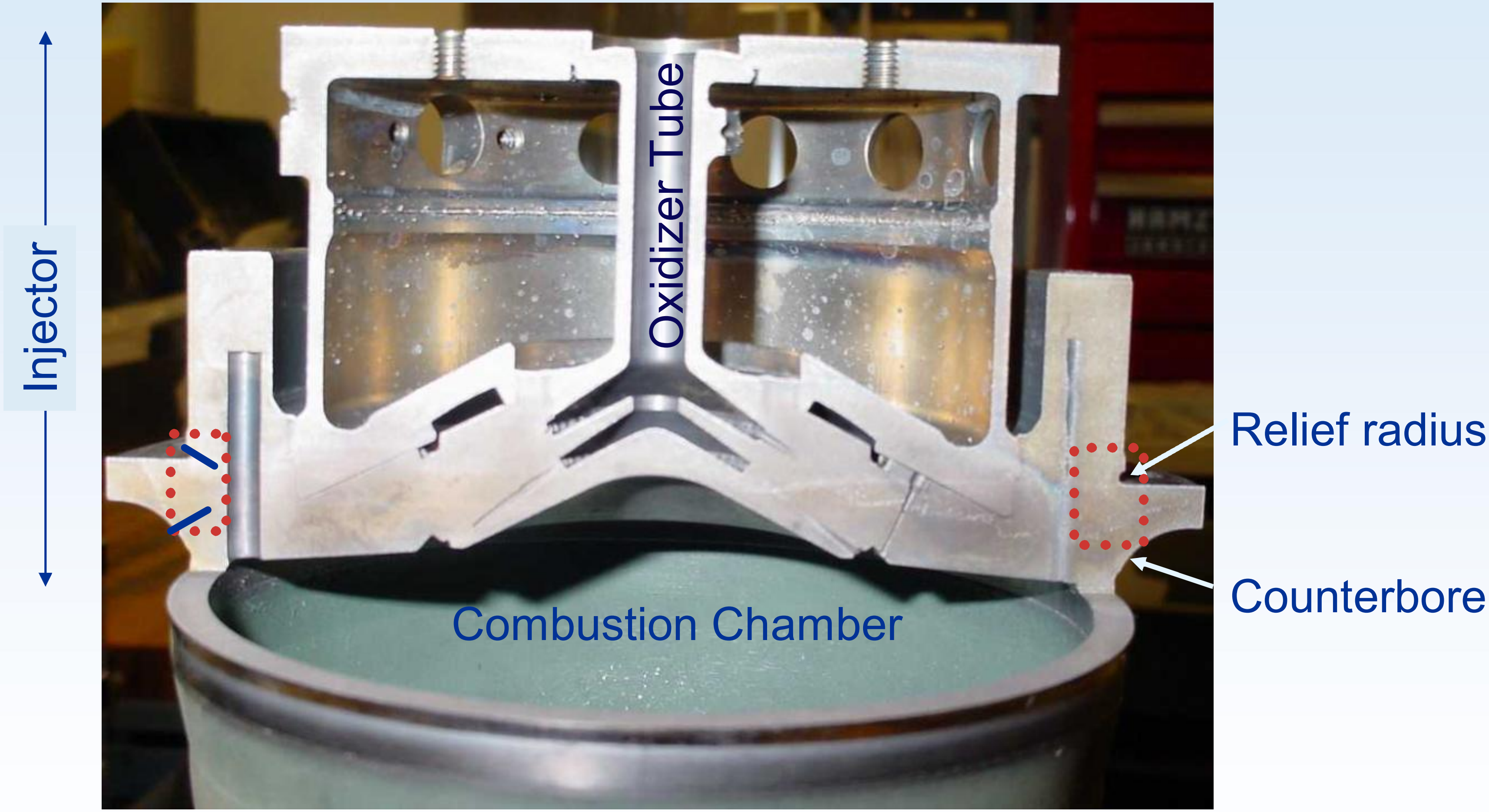


Relief radius cracks

Photos from Boeing-Huntington Beach

Cut-Away View of a Thruster

Location of Cracking is Shown in Red Boxes



Concern was that hot combustion gases may leak through the cracks and adversely affect the orbiter vehicle

Photo from Boeing-Huntington Beach

Thruster Cracking Background

- Seven thrusters were found to contain cracks between 1979-1982
  - Found after failing an external leak test after qualification testing
  - Manufacturer developed an ultrasonic inspection technique to screen out cracked thrusters before service
  - It was believed at that time that all cracked thrusters were detected and removed from service
- Thrusters are leak checked every 8 missions but are not directly inspected for cracks because cracking locations are inaccessible.
- In April 2004, a thruster (Serial Number (S/N) 120) was found to contain multiple cracks after its combustion chamber was repaired and refurbished.
  - S/N 120 was the fleet leader for number of firings and flew 29 flights
  - The old 1979 inspection apparatus was recovered and used on S/N 120. Inspection technique was unable to detect any cracking, despite the fact that the cracks extended 270 degrees around the circumference.
- Thruster cracking was a serious issue due to high criticality of component and was considered a "Crit 1/1" failure

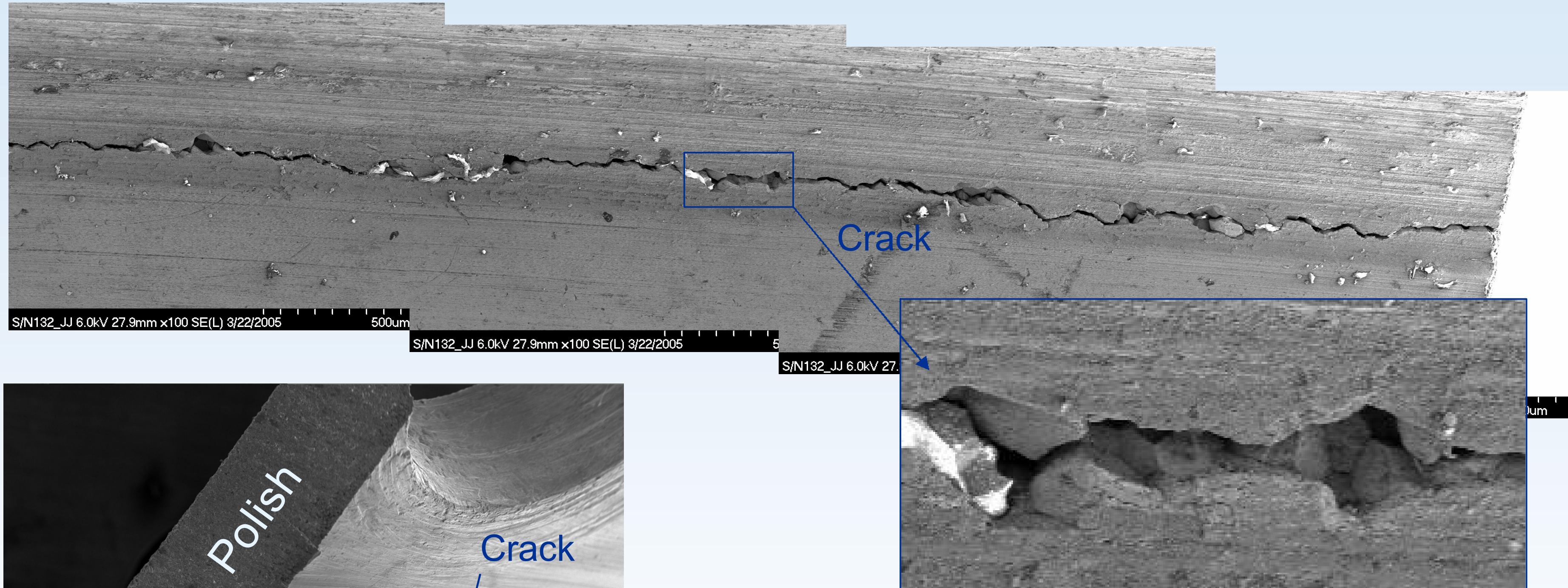
NESC Materials Effort

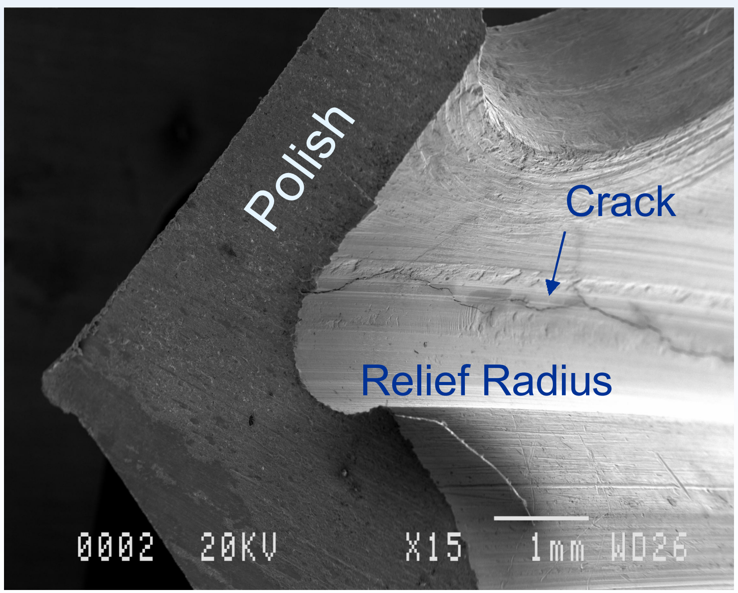
- In April 2004, NESC was requested to be a consultant to the Orbiter Project Office (OPO) team that was investigating cracking in S/N 120
- NESC conducted detailed reviews of the relevant niobium literature and historical thruster documentation from 1979-1982.
  - Literature provided strong evidence that niobium was susceptible to hydrogen embrittlement and interstitial (oxygen) contamination
  - Lack of substantiation for conclusions in historical thruster reports
- In July 2004, Boeing-Huntington Beach completed their failure analysis for the OPO
  - Could not identify age of the cracks
  - Questions remained open: Were the cracks old (i.e, from the manufacturing process), or were the cracks growing in service? Could we safely operate the thrusters?

NESC Materials Effort

- In July 2004, the NESC team identified new materials characterization and mechanical tests focused specifically on determining:
  1. Root cause of thruster cracking
  2. Likelihood of crack propagation in service
     - If root cause was hydrogen embrittlement, then water ingress into existing cracks could continue to provide a source of hydrogen in service
- NESC proposal was met with vigorous opposition from NASA-JSC and contractor engineers
- After four months of continued advocacy to JSC, they agreed that the new work by NESC team should be performed

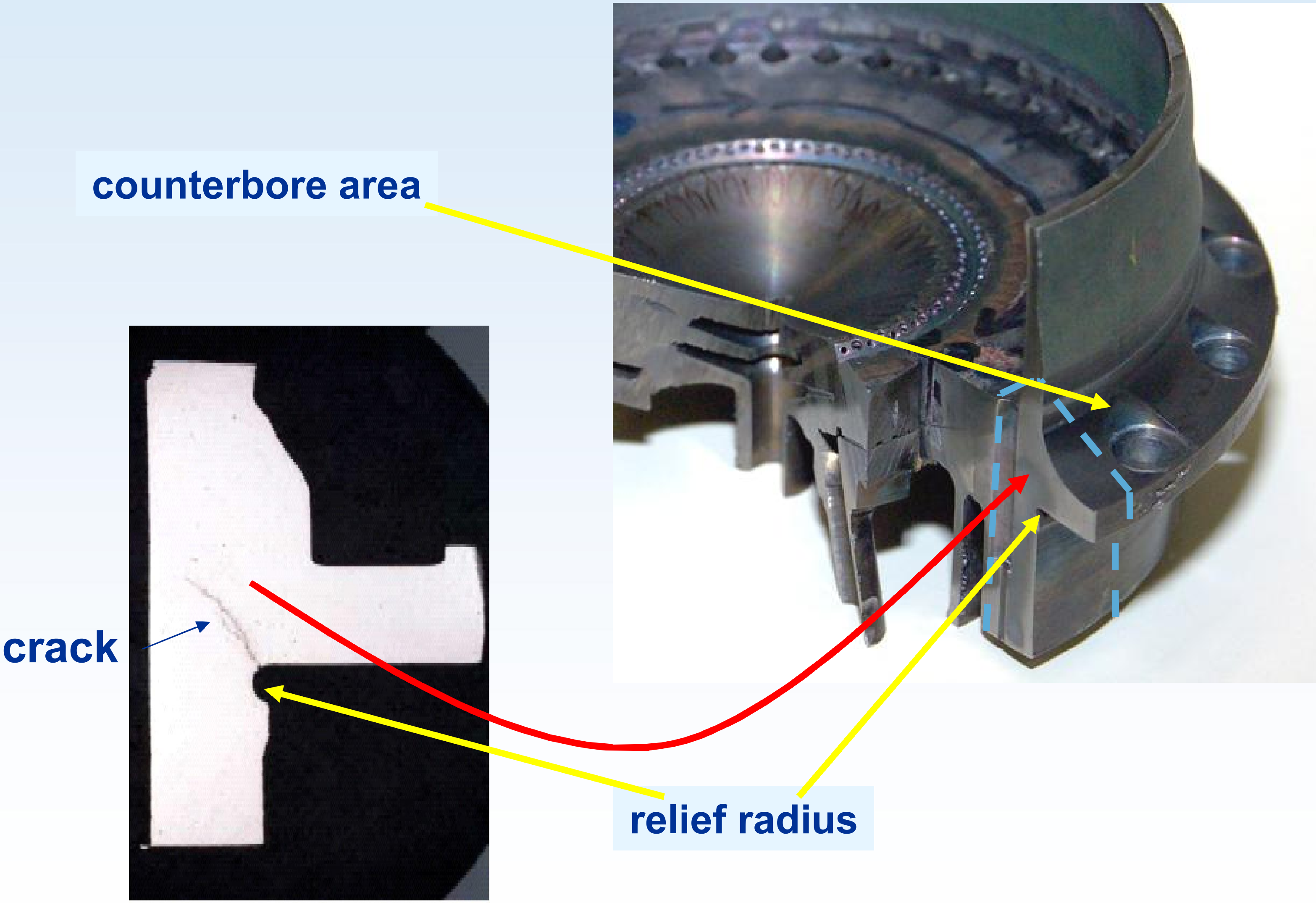
Cracks on the Surface of the Thruster Hardware Appeared to Follow Grain Boundaries



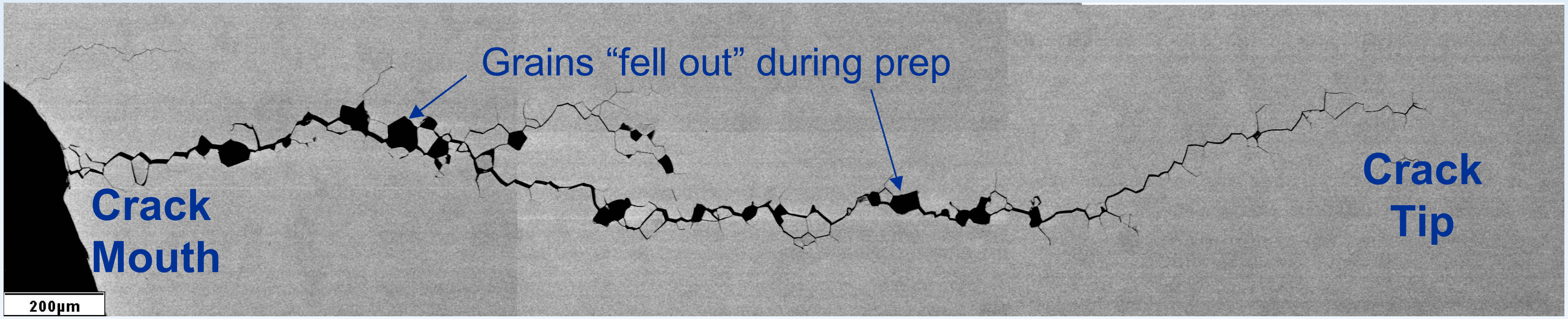


Further characterization was performed:
1) Polish thruster sections and examine crack mode and chemistry
2) Open up cracks and analyze their surfaces

Sections of Thruster Hardware Were Machined and Metallographically Prepared for Examination



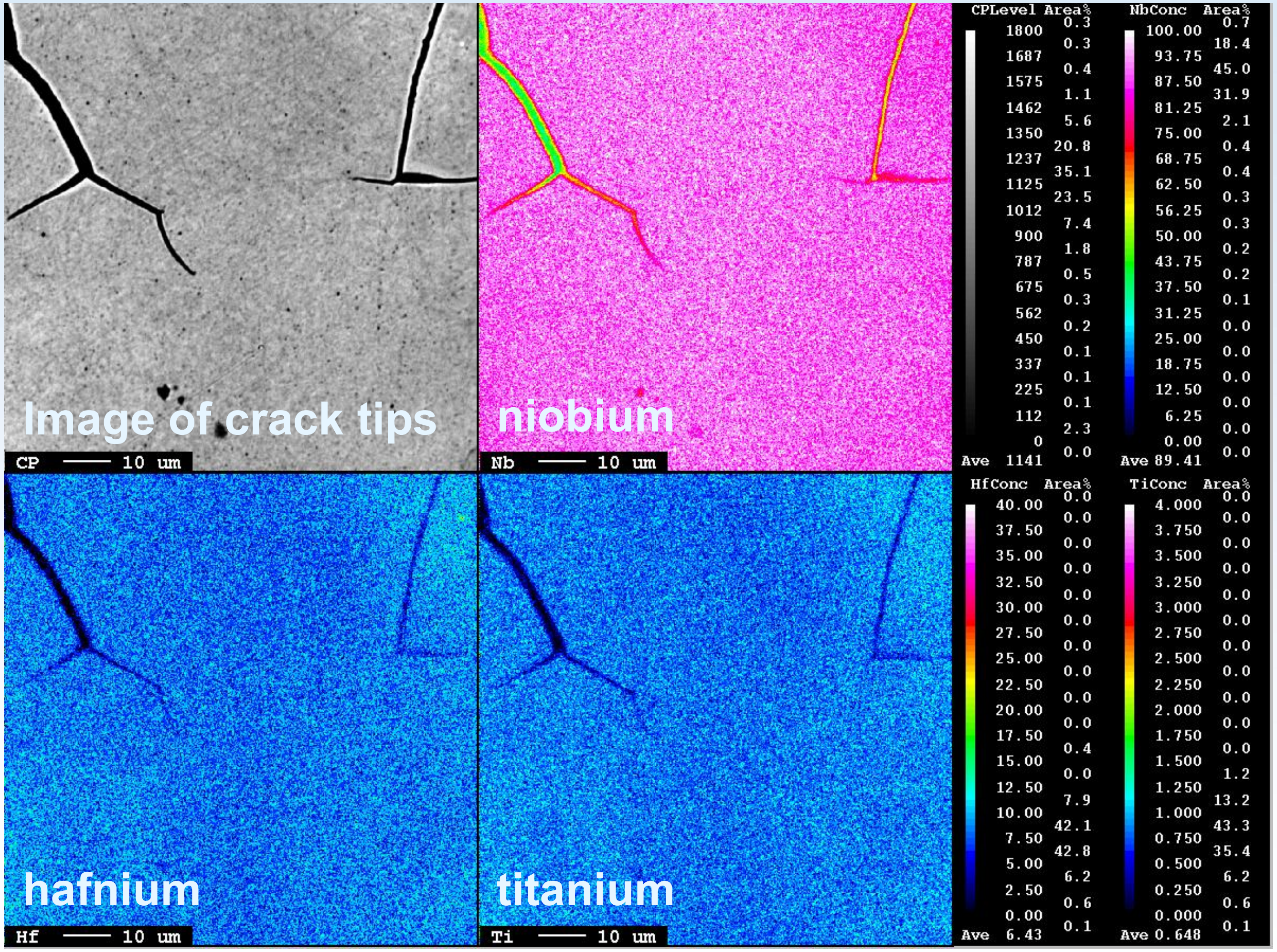
Detailed Microstructural Analyses Were Performed at Crack Mouth and Crack Tips



Cracks are Intergranular and Follow the Grain Boundaries

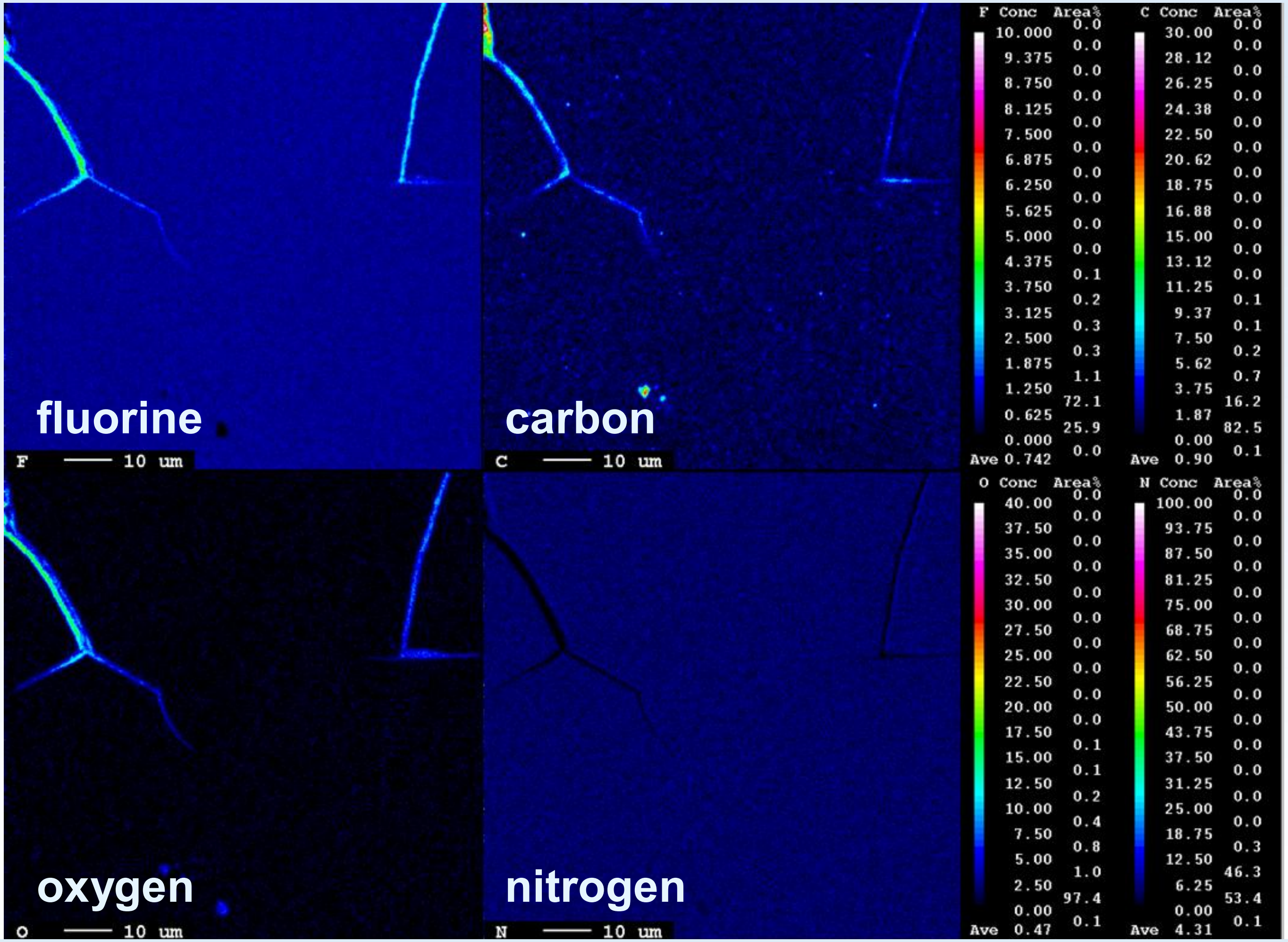
- Examine chemistry of reaction products within crack
- Compare chemistry and alloy microstructure along the crack, ahead of crack, and in areas away from cracks

Electron Microprobe Indicated that the Major Elements Did Not Segregate Along the Grain Boundaries



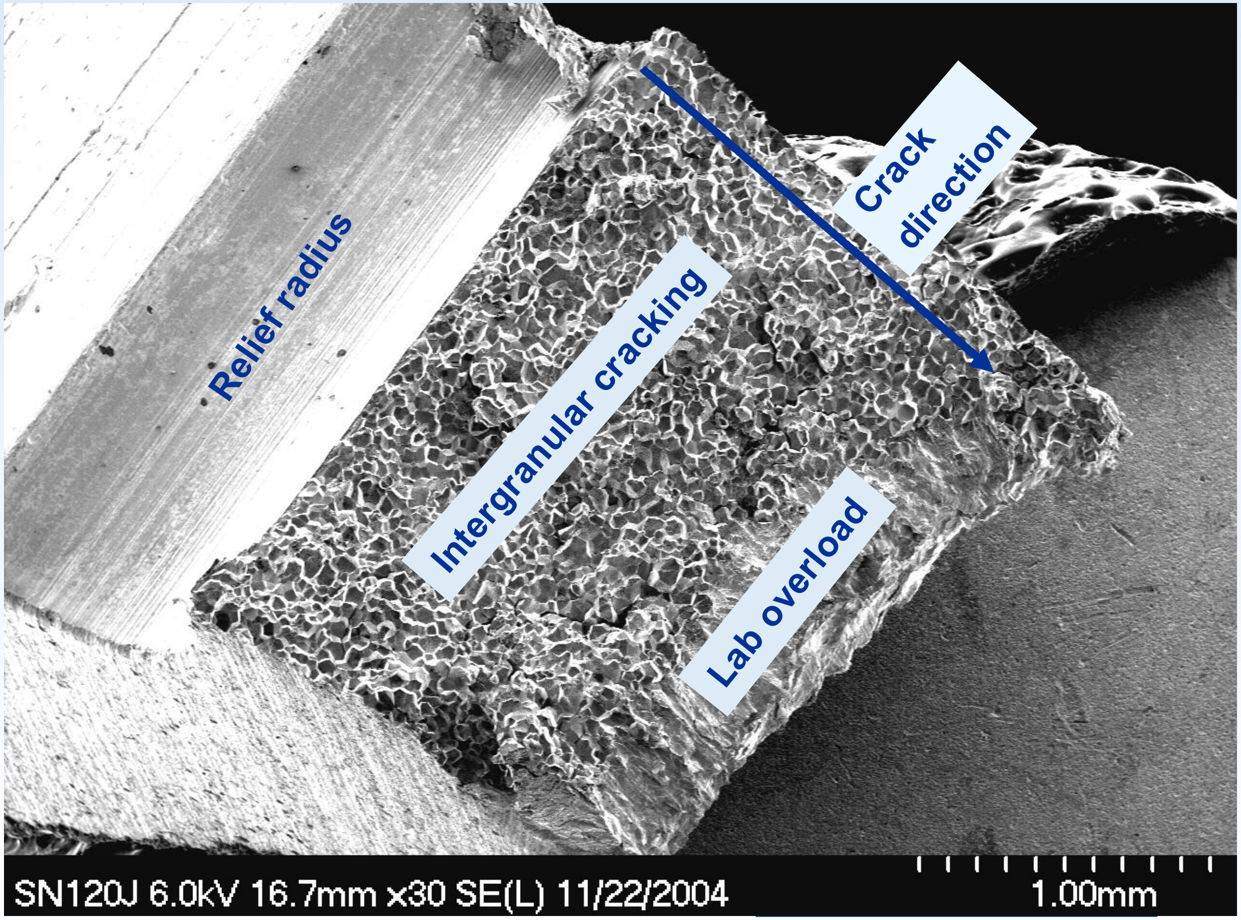
Eliminated Hot Salt Stress Corrosion as a Potential Root Cause

Chemistry Within Cracks Is Consistent with Reaction Products from Manufacturing



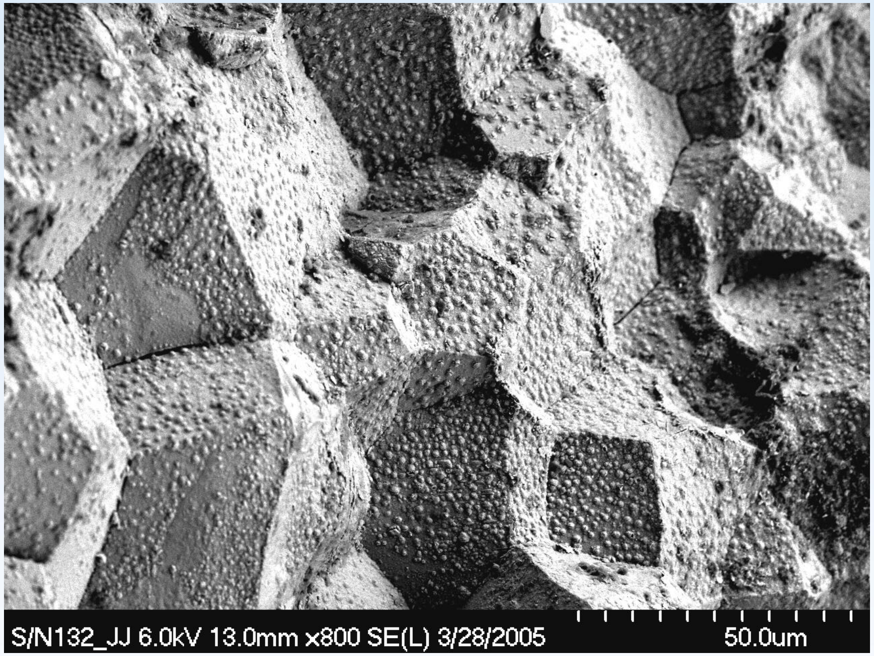
Fluorine came from pre-weld etchant. Carbon and oxygen were introduced during bake out after welding. No interstitial contamination ahead of cracks. Next step involved examination of broad expanses of crack surface.

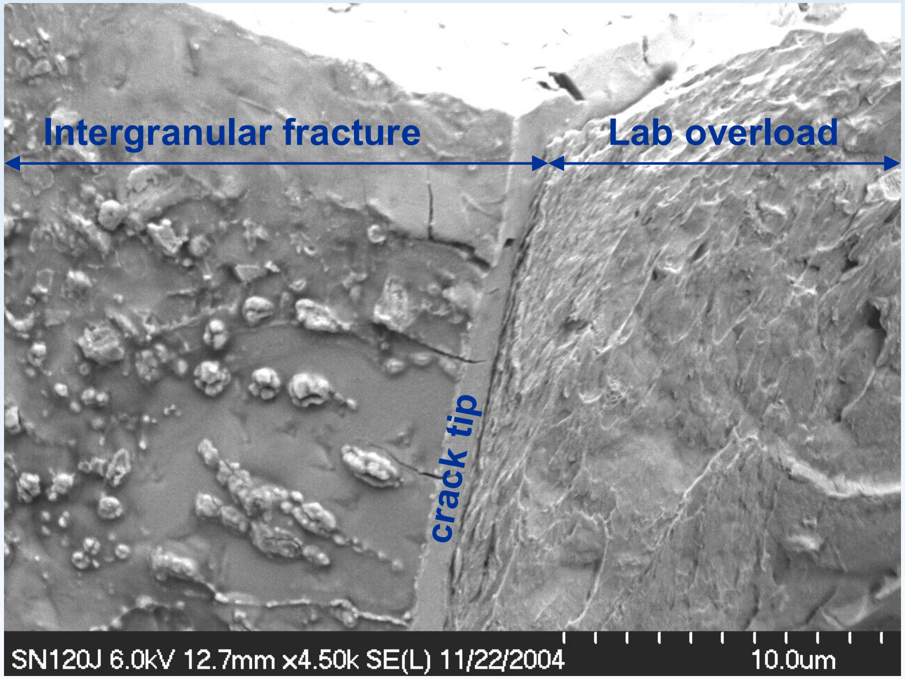
Entire Fracture Surface of Crack Was Intergranular
No change in crack mode



Higher magnifications were employed to examine fracture for evidence of crack growth

Exhaustive Quantitative Analyses on Thruster Cracks Provided No Evidence for Crack Growth in Service

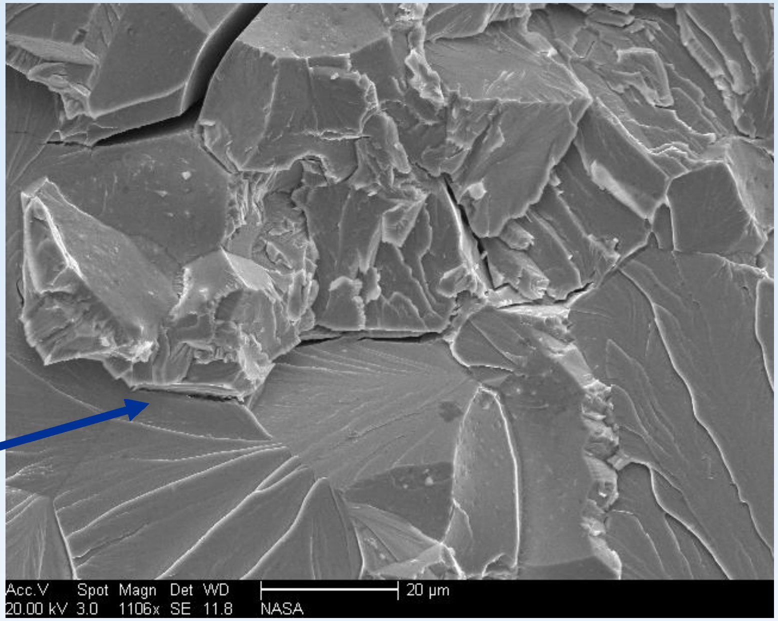




- *No significant changes were observed in crack features or reaction products from crack mouth to crack tip*
- *State of the oxide did not change over the crack depth, which suggests that the crack did not grow slowly over time in service*
- *Lab tests demonstrated that popcorn oxide forms on niobium during manufacturing bake out in air when cleaning etchants are present*

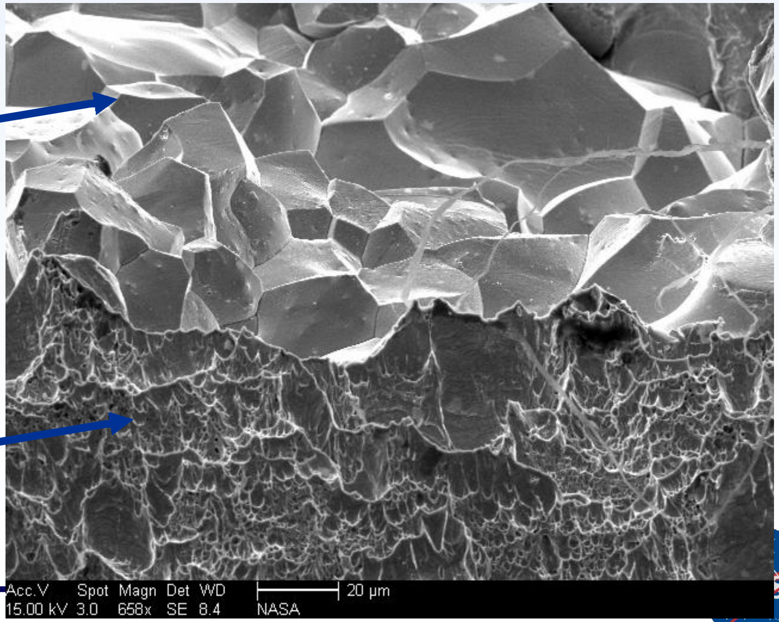
Mechanical Tests Were Performed to Determine Behavior of Niobium in Presence of Hydrogen

- High levels of hydrogen cause hydrides to form, which resulted in transgranular cleavage

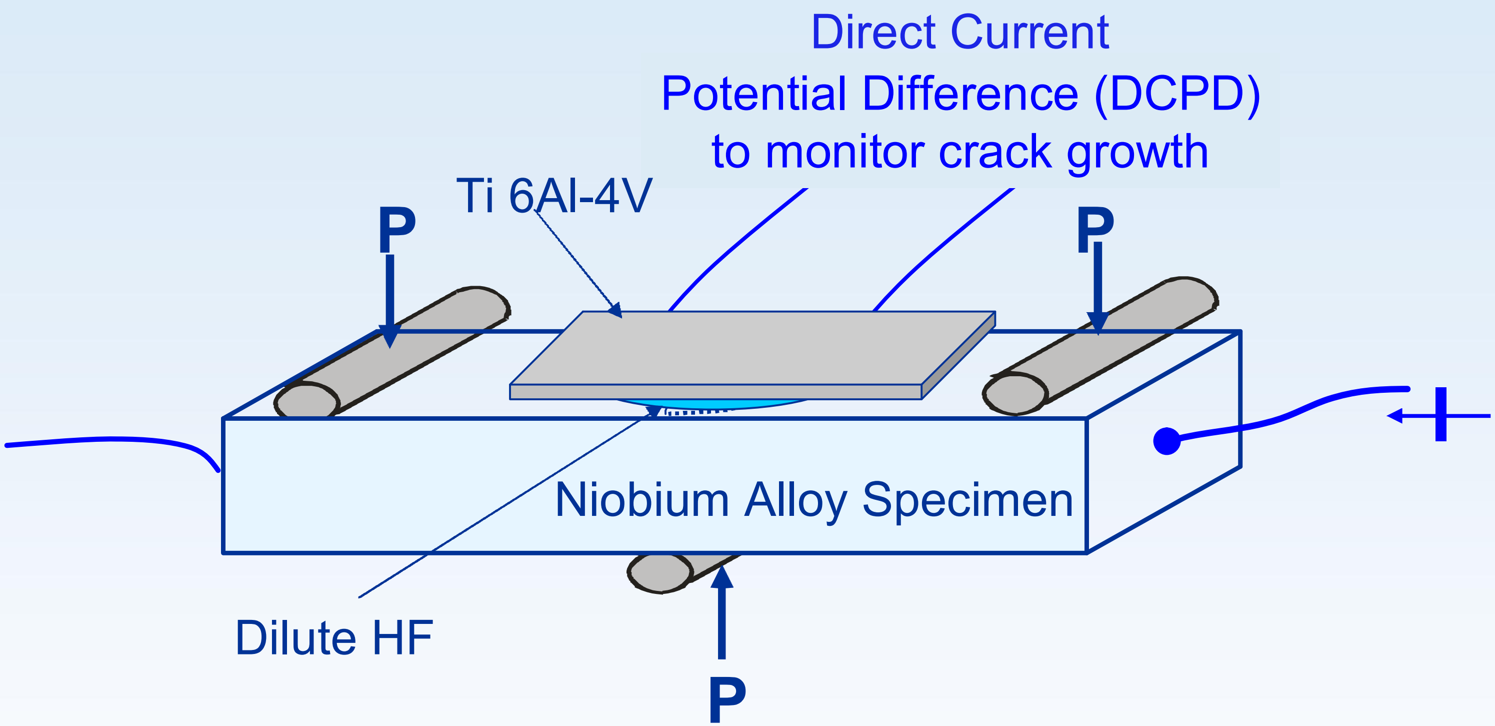


- Lower levels of hydrogen caused intergranular cracking

- Very low levels of hydrogen produced ductile failures

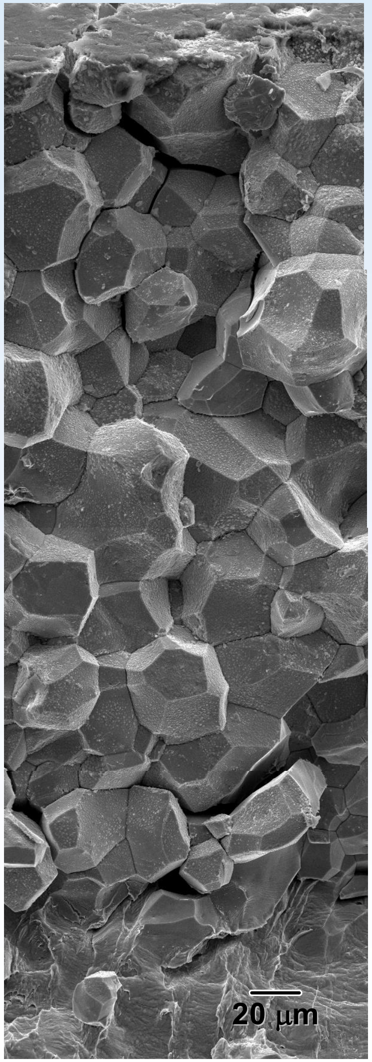


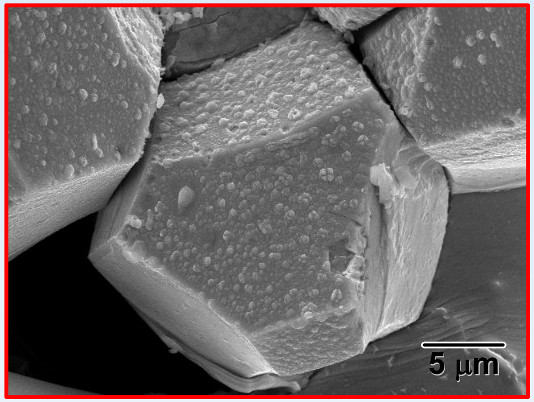
Bend Test Specimen Designed to Closely Simulate Loading Condition in Thruster Hardware



- Simulated thruster manufacturing:
  - Applied stress, then etchant and Ti sheet, and held at RT/36hr
  - Bakeout in air at 600F/48hrs under stress
- Simulated in-service exposure:
  - Attached wires and added environmental cell, exposing stressed specimen to moist air environment (>70% relative humidity)

Simulation of Thruster Processing on Test Specimens Reproduced the Fracture Mode Observed in Thruster Hardware

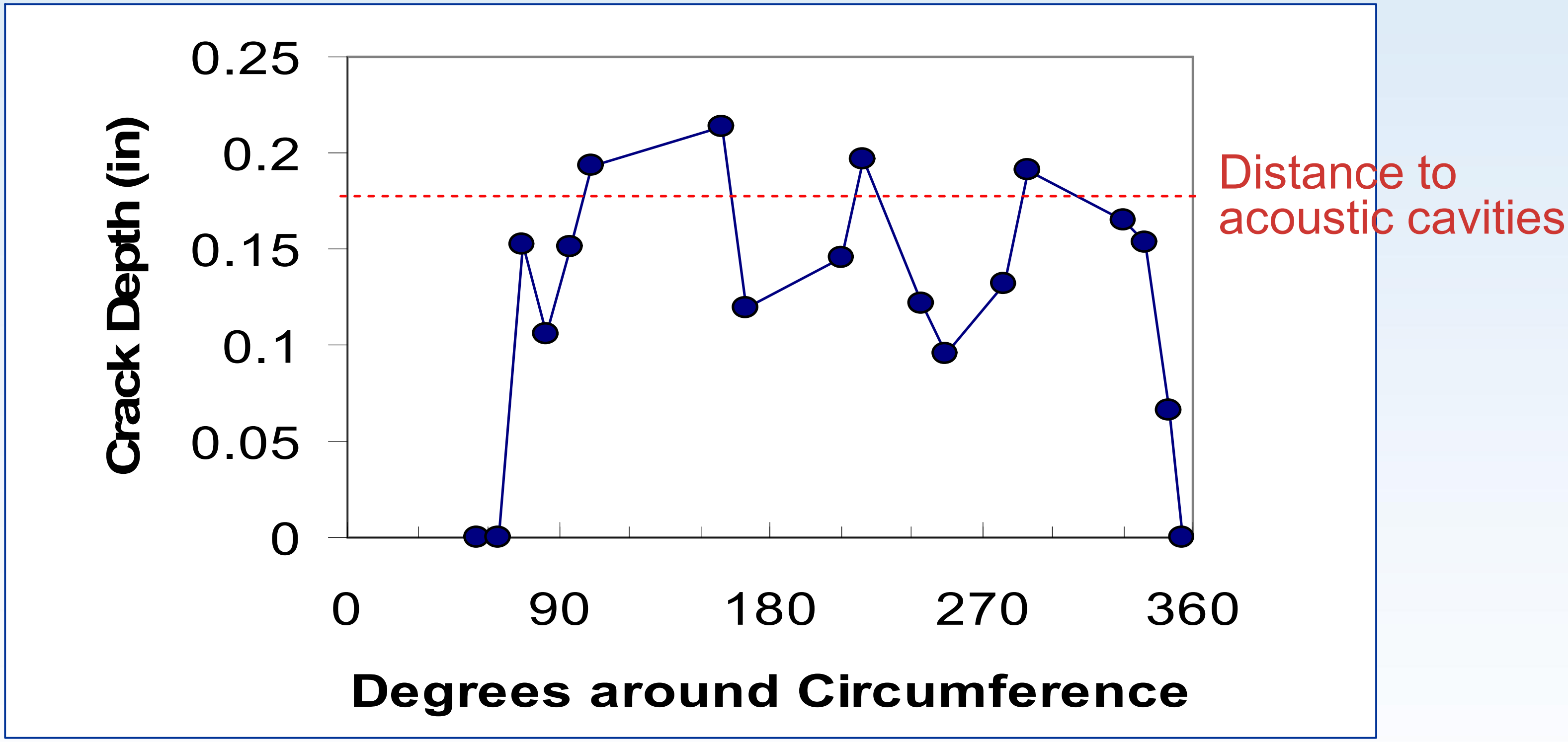




Long term testing of a cracked specimen in a moist air environment showed no evidence of crack growth

Demonstrates that water ingress into existing thruster cracks is unlikely to cause further crack growth

NESC Destructive Analyses Indicated Significant Relief Radius Cracking in S/N 132



Crack depth profiles were provided to Boeing for fracture analysis which indicated that the thrusters have a remaining life that was well in excess of 8-mission maintenance cycle where helium leak checks are performed.

NESC Findings

- Thruster cracking occurred during original manufacturing process
  - Due to inadequately rinsed, HF-containing etchant that was followed by a 600°F bakeout in air
  - Inspection procedures did not prevent cracked thrusters from entering the fleet
- Cracking was the result of hydrogen embrittlement
- No evidence for appreciable crack growth in-service
  - Based on lab testing and exhaustive examinations of thruster hardware crack surfaces

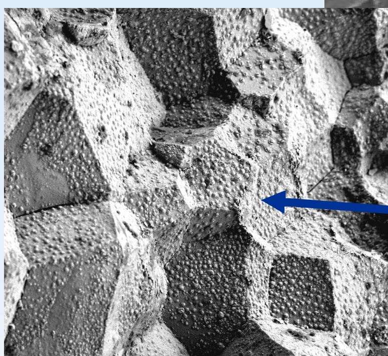
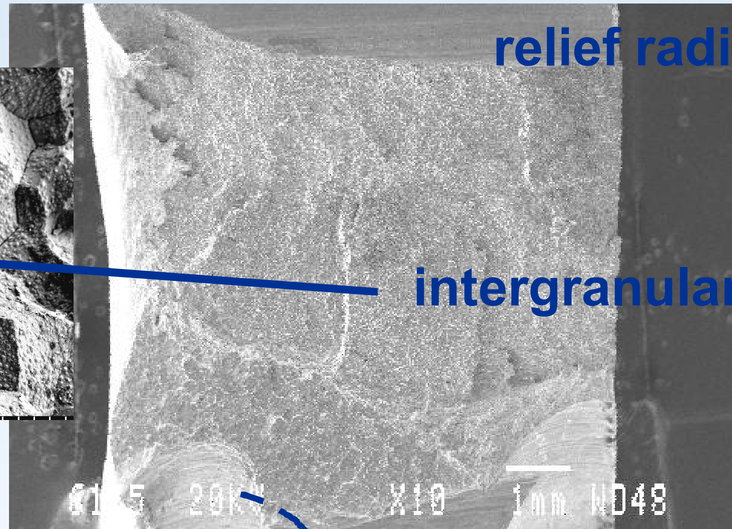
↓

We thought we were done and then….

Thruster Rejuvenation Processes at WSTF Were Being Performed Incorrectly

- Since 1999, White Sands Test Facility (WSTF) had been immersing thrusters into NaOH solution (sometimes at double the concentration), instead of following the design process of swabbing the surface prior to welding
- Two of the ten thrusters that had undergone this erroneous processing were installed on Discovery for STS-114, and Discovery was going to be rolled out to the pad
- NESC reviewed niobium literature which indicates that NaOH causes hydrogen embrittlement under many conditions
- Exposure levels used at WSTF was in the range that causes embrittlement
- Question: Could this erroneous immersion embrittle the uncracked regions of niobium thrusters?

Boeing Fractography Showed Transgranular Cleavage Ahead of the Relief Radius Crack in S/N 120

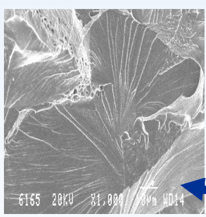
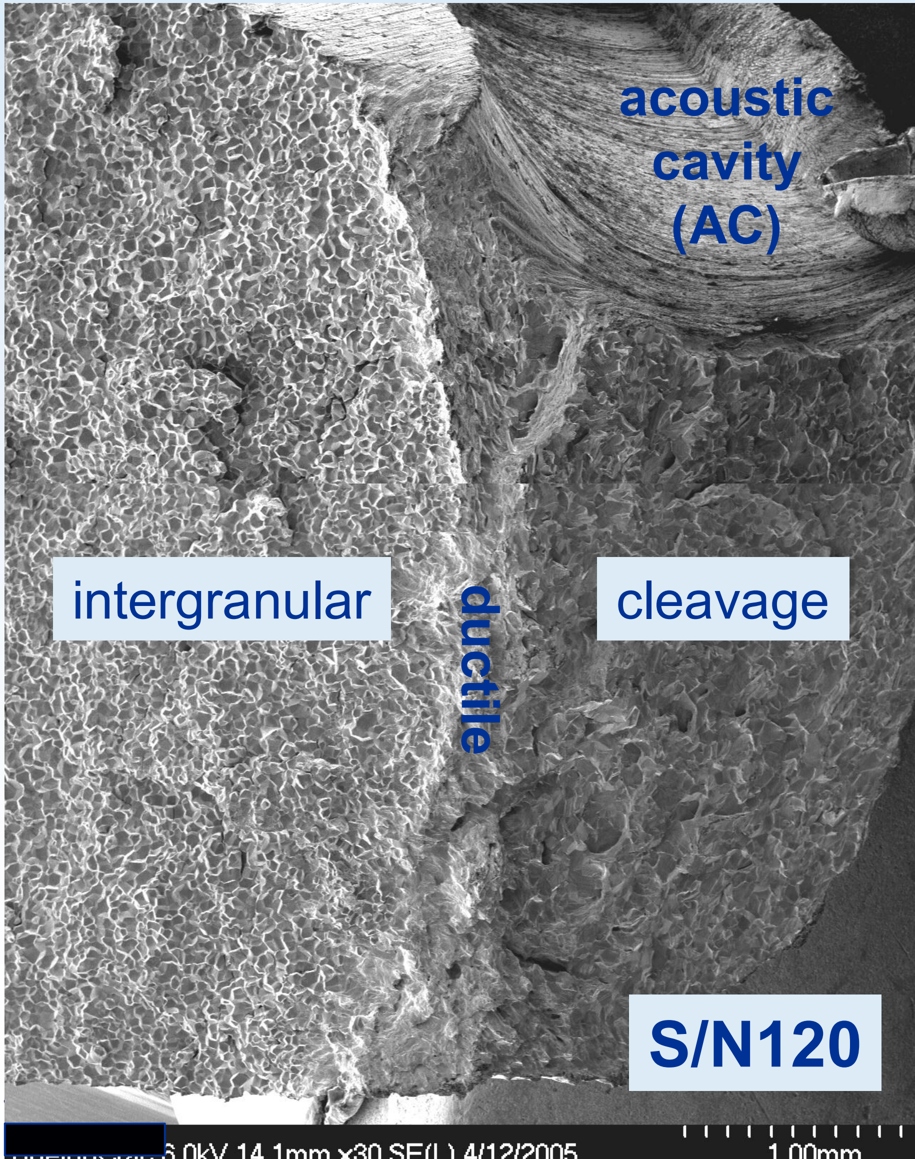
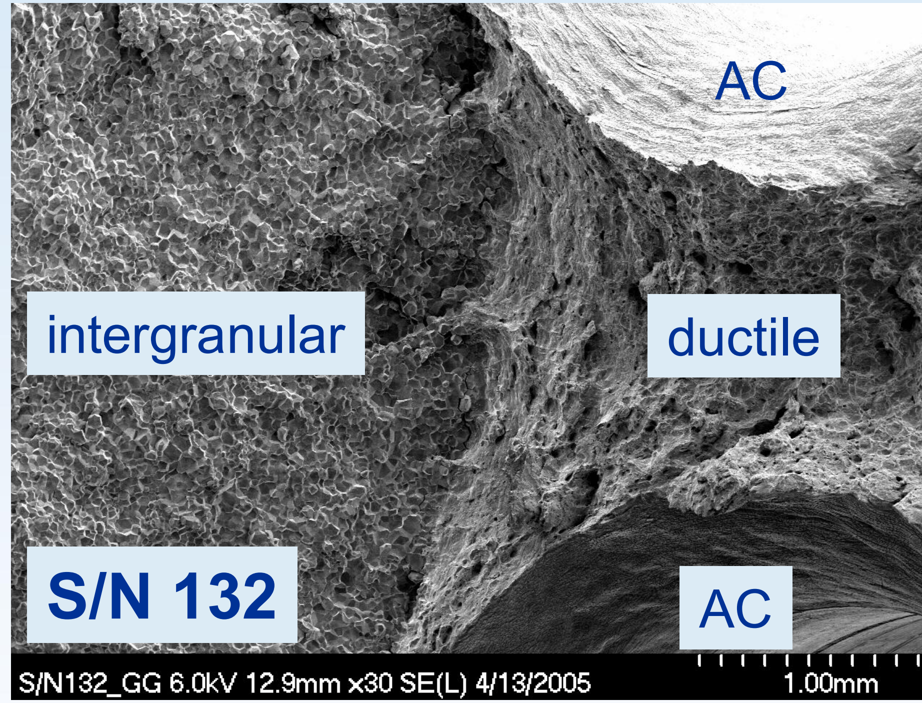


Photo from Boeing-HB final report

Niobium is normally a ductile material; cleavage was not expected

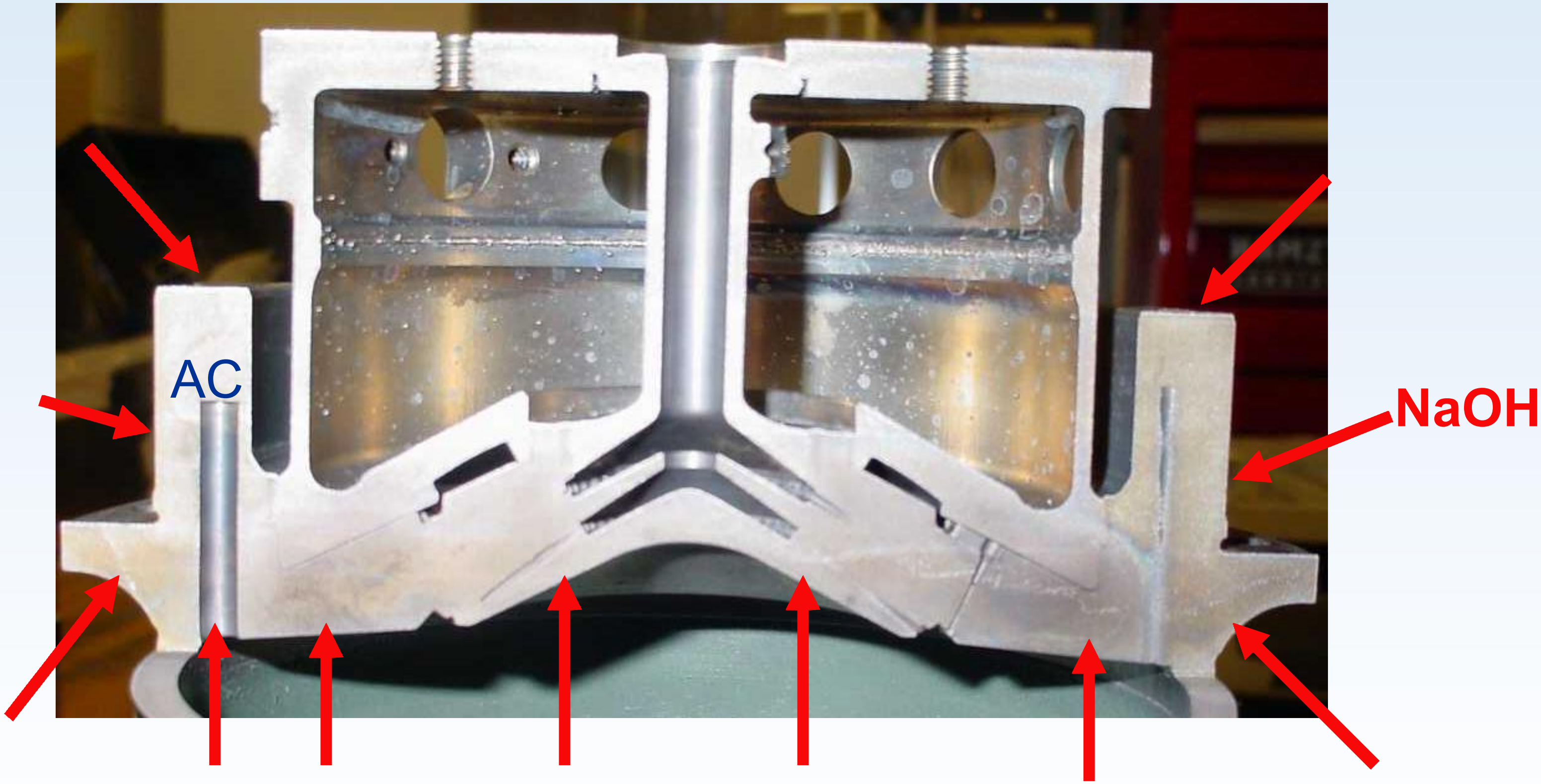
GRC Fractography Showed Transgranular Cleavage in S/N 120 But Not in S/N 132





- *S/N 120 was a rejuvenated thruster and was immersed in NaOH*
- *S/N 132 was never rejuvenated and was not exposed to NaOH*

NESC Concern was that NaOH Immersions Could Be Bulk Charging Rejuvenated Thrusters with Hydrogen on All External Surfaces



Earlier NESC Lab Testing Showed High Levels of Hydrogen Caused Brittle Transgranular Cleavage Failures

Flight Constraint was Imposed on STS-114 as a Direct Result of GRC's Work

- The Shuttle doesn't fly until the unacceptable risks that caused the flight constraint get addressed.

- NESC, WSTF, OPO, and Boeing met for a week at WSTF to identify the controlled tests that needed to be performed to evaluate the effects of NaOH exposures
- A series of nominal and worst-case immersions were performed on spare thrusters
- Exhaustive testing and microstructural analyses were performed on exposed and unexposed thruster material
- Fractography showed small areas of transgranular cleavage
- Test data showed slightly reduced mechanical properties in exposed thruster material but the decreases were considered to be small based on subsequent fracture analysis

Final Thruster Disposition

- Testing and fractography enabled an informed engineering decision to be made regarding impact of erroneous rejuvenation processes
- Flight constraint was lifted, and NESC helped Orbiter M&P Group to develop sufficient flight rationale for the thrusters' continued use
- All thrusters were cleared for remaining shuttle missions, and leak checks will be performed after every eight missions
- Thruster rejuvenation processes at WSTF were modified to ensure that NaOH immersions were completely eliminated, in order to reduce risk of additional hydrogen uptake in rejuvenated thrusters

Lessons Learned

- Original engine manufacturer did not adequately certify the inspection technique when it was first deployed
  - Critical that the reliability and reproducibility of inspection techniques be firmly established
- Process "creep" occurred with rejuvenation procedures
  - Mid-life certifications may be a value-added opportunity for identifying process creep and for incorporating new/increased knowledge of material behaviors and updating acceptable practices
- Difficult to get original materials certification documentation (chemical analyses, mechanical property data, processing records, etc.) which are usually maintained by original manufacturer
  - Making such documentation of *high criticality* components a <u>contract deliverable</u> to NASA should enable the agency to access and use the data more efficiently